

A MODEL TO ESTIMATE THE COST EFFECTIVENESS OF INDOOR ENVIRONMENT IMPROVEMENTS IN OFFICE WORK

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June 2004

This work was supported by the Finnish Technology Agency and Finnish Occupational Health Fund, project Productive Office 2005. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technology Program of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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ABSTRACT

Deteriorated indoor climate is commonly related to increases in sick building syndrome symptoms, respiratory illnesses, sick leave, reduced comfort and losses in productivity. The cost of deteriorated indoor climate for the society is high. Some calculations show that the cost is higher than the heating energy costs of the same buildings. Also building-level calculations have shown that many measures taken to improve indoor air quality and climate are cost-effective when the potential monetary savings resulting from an improved indoor climate are included as benefits gained. As an initial step towards systemizing these building level calculations we have developed a conceptual model to estimate the cost-effectiveness of various measures. The model shows the links between the improvements in the indoor environment and the following potential financial benefits: reduced medical care cost, reduced sick leave, better performance of work, lower turn over of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality and climate. The pathways to these potential benefits from changes in building technology and practices go via several human responses to the indoor environment such as infectious diseases, allergies and asthma, sick building syndrome symptoms, perceived air quality, and thermal environment. The model also includes the annual cost of investments, operation costs, and cost savings of improved indoor climate. The conceptual model illustrates how various factors are linked to each other.

SBS symptoms are probably the most commonly assessed health responses in IEQ studies and have been linked to several characteristics of buildings and IEQ. While the available evidence indicates that SBS symptoms can affect these outcomes and suggests that such a linkage exists, at present we can not quantify the relationships sufficiently for cost-benefit modeling. New research and analyses of existing data to quantify the financial importance of SBS symptoms would enable more widespread consideration of the effects of IEQ in cost benefit calculations.

KEYWORDS

indoor environment, ventilation, thermal environment, productivity, sick leave, modeling, costs, benefits, SBS-symptoms

INTRODUCTION

Increased evidence shows that indoor environmental conditions substantially influence health and productivity. Building professionals are interested in improving indoor environments and quantifying the effects. Macro-economic estimates of nationwide gains have been developed. They show that the potential benefits from indoor environmental improvements for the society are high (Fisk 2000, 2001, Mendell et al. 2002). Some calculations show that the estimated cost of deteriorated indoor environment is higher than the heating energy costs of the same buildings (Seppänen 1999). Potential health and productivity benefits are not yet generally considered in conventional economic calculations pertaining to building design and operation. Only initial cost, and energy and maintenance costs are typically considered. A few sample calculations have also shown that many measures to improve indoor air environment are cost-effective when the health and productivity benefits resulting from an improved indoor climate are included into the calculations (Djukanovic et al. 2002, Fisk 2000, Hansen 1997, Seppänen et al. 2000, Tuomainen et al. 2002). There is an obvious need to develop tools and models so that economic outcomes of health and productivity can be integrated in cost benefit calculations with initial, energy and maintenance costs. The use of such models would be expected to lead to improved indoor environments, health and productivity.

To systemize these building level calculations we developed a conceptual model to estimate the cost-effectiveness of retrofits of indoor environment. The model shows the links between the improvements in the indoor environment and potential benefits. We have quantified also the links between ventilation and sick leave (Fisk et al. 2004), and high temperature and productivity (Seppänen et al. 2004). We also review evidence linking SBS symptoms with sick leave and productivity.

THE CONCEPTUAL MODEL

Structure

The basic idea of the model (Figure 1) is to illustrate the most important cost and benefit items and the linkages which should be included in costs-benefit estimates of design changes, retrofits or building operation changes that affect the indoor climate. The model shows the links between the improvements in the indoor environment and potential benefits. The model also includes the annual cost of investments, operation costs, and cost savings of improved indoor environment.

In the model, input data plus design or retrofit measures (Box #1) leads to an improvement in one or more indoor environmental conditions (e.g. reduced pollutant concentration), which in turn influences on one or more human responses (Boxes #3-9), such as a health condition, level of comfort or complaint frequency. Human responses are linked to benefit categories (Boxes #10-14) such as health care, sick leave days, and responses of facility management to complaints. Finally, the benefit categories are linked to economic gains (Boxes #15-19). The arrows between boxes represent quantitative mathematical functions that link conditions or outcomes in the two boxes. The human responses to the implemented measure for improvement are a consequence of improvements in indoor environmental conditions (#2); however, in some cases available data directly links a building feature or operational practice directly to a human response without a quantification of the change in indoor environmental conditions. Other data directly links a building feature or practice, or an environmental condition (e.g., temperature) directly to work performance without an intermediate health effect or environmental condition to performance without a known impact on health or complaints. These types of linkages are not shown in the Figure 1.

The use of the model starts from the selected measure for IEQ improvement measure (Box #1) in the figure 1. These measures may include better control of temperature, better ventilation, control of pollutant sources, etc. To evaluate the cost effectiveness of any measure, the investment and operation costs are also needed for the selected measure as an input value. The effect of the measure on IEQ depends upon the pre-existing level of IEQ. For example, the magnitude of pollutant concentration reductions obtained by increasing ventilation rates will be affected by the initial rate of ventilation and the strength of pollution sources in the building. Existing mass balance or energy models can often be used to estimate how the building design or operation affects IEQ conditions, e.g., pollutant levels or temperatures. However, some changes in IEQ, such as changes in bioaerosol concentrations, will be very difficult to quantify with available information and models. In general, new models and supporting data are needed to relate IEQ condition with human responses.

Many IEQ-improvement measures affect only a section of the building housing a subset of all occupants. The cost benefit calculations must consider only the affected occupants. Normalization of economic outcomes per unit floor area will often facilitate comparisons with other measures.

Economic IEQ model for the owner occupied existing buildings

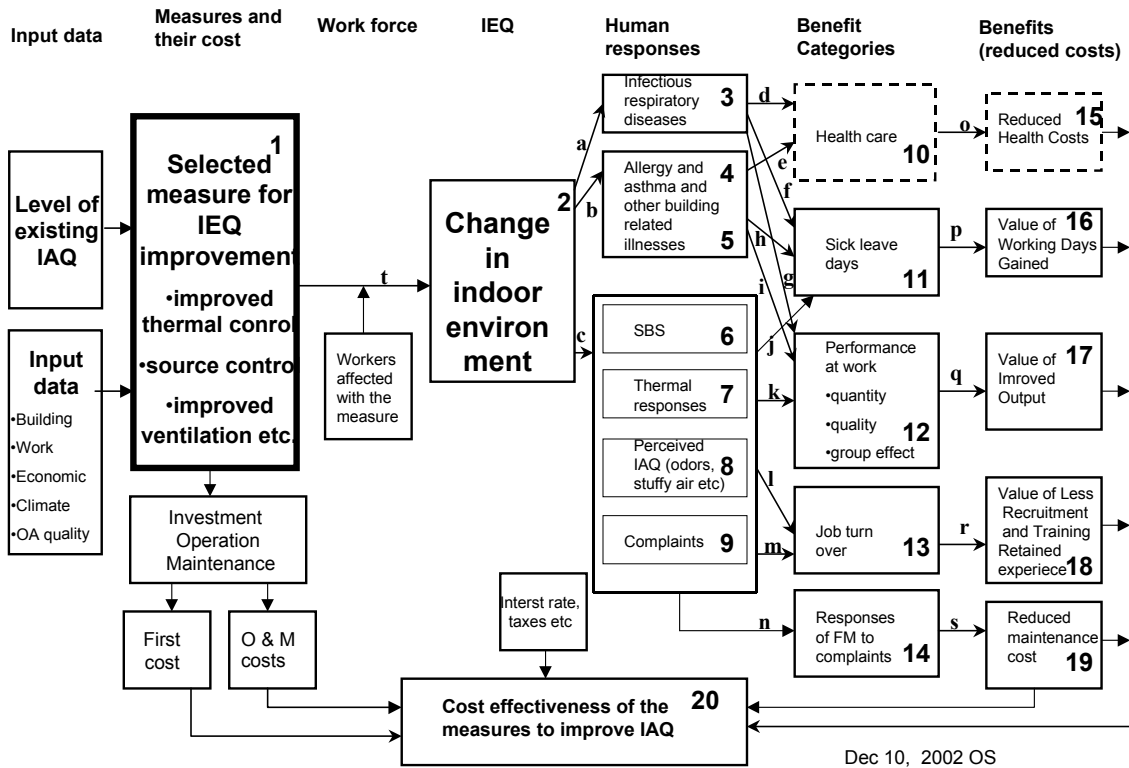


Figure 1 Economical IEQ model for owner occupied buildings. The model illustrates the linkages between building and potential benefit categories due to improved indoor environment.

Human responses

Adverse human responses (#3-9) to the indoor environment range from infectious diseases to complaints. The evidence of the effect of indoor environment on these human responses varies with outcome.

Some infectious respiratory diseases (#3) are known to be transmitted, in part, by aerosols. These diseases include such as common colds (e.g. rhinovirus infections), influenza, and adenovirus infections. In the United States, four common respiratory illnesses (common cold, influenza, pneumonia and bronchitis) cause 176 million days lost from work and additional 121 million working days of substantially restricted activity (Fisk 2000).

Although the primary causes of asthma and allergy (#4) are not necessarily related to buildings, the prevalence and severity of symptoms are commonly related to building factors. The cost of allergy and asthma is high, estimated to be only in the US \$15 billion per year (Fisk 2000). Other building related illnesses (#5) include humidifier fever, Legionnaire's disease, heart and lung diseases due to environmental tobacco smoke, and lung cancer due to radon exposure.

SBS symptoms (#6) are probably most commonly used outcomes in health-related building studies. The representative data from US office buildings found that 23% of office workers (15 million workers) reported two or more frequent sick building syndrome symptoms that improved when they were away from the work place (Fisk 2000).

The thermal environment (#7) is not ideal in many buildings. Shortage of cooling or heating capacity, high internal or external loads or poor control systems may lead to unacceptable temporal or spatial variation of the temperatures in a building. The relation between building design and operation, and thermal conditions is established with many building simulation tools. Some of these tools estimate for human comfort. While criteria for thermal comfort are well established, the thermal environment may also have a direct link to work performance and thermal conditions may affect SBS symptoms through an unknown mechanism. Figure 1 does not show all of these linkages.

Perceived indoor air quality (PAQ) (#8) has been commonly used as a metric of human response to indoor air quality, and ventilation rates. It can be evaluated in real buildings semi-quantitatively with trained or untrained olfactory panels. Many ventilation standards are based on the dilution of body odor by ventilation and the resulting PAQ. Perceived air quality is affected mainly by pollution sources in the building, ventilation rates, outdoor air quality, and air temperature and humidity.

Complaints about indoor environments (#9) to facility management are very common. Federspiel (2001) has shown that responses to temperature-related complaints impose a significant cost in office buildings.

Linkages Between Building Features, IAQ and human responses

Depending on the factor on which the indoor environmental improvements are focused, the pathways from indoor environment to benefits vary. The links of building features to productivity are normally neglected; however, modification of building features will often change indoor environmental conditions, which may change health and, in turn, affect productivity. To use the model, we normally require quantitative estimates of how a design change or building retrofit influences indoor environmental conditions and, in turn, quantitative estimates (indicated by functions d-n in the Figure 1) of how these conditions affect health, absence, performance, and other financially important outcomes. The conceptual model illustrates how various factors are linked to each other. After a review of existing literature, it became apparent that better data are needed for nearly all links (d – n) between environmental conditions and human outcomes. However, we do not necessarily need to quantify all functions as some data are available linking directly a change in building design (HVAC system type) or operation (ventilation rate) to a health or performance outcome. In the following we summarize the information available on these links

IEQ-infectious diseases

The relation between the indoor environment and airborne transmission of infectious diseases is shown in several studies Fisk (2000) and supported by the theoretical model (Riley 1980, Nardell et al. 1991). Fisk (2000) concluded that improvements in the indoor environment may reduce the sick leave due to infectious diseases up to 9-20 %. The prevalence of infectious diseases seem to be affected by the ventilation rate as summarized by Seppänen et al. (1999) and by occupant density (Jaakkola and Heinonen 1995). Milton (2000) found that higher ventilation rates were associated with reduced short-term absence, much of which is caused by respiratory illnesses. Fisk et al. (2003 and 2004) show how a relationship between air change rate and absence from work due to short-term sick leave can be estimated by combining experimental data and a theoretical model.

IEQ-humidifier fever

The humidifier fever refers to a syndrome with common-cold type symptoms such as fever, respiratory tract symptoms, and fatigue. It has been associated with microbes or their metabolic products released from contaminated humidifiers. In contaminated working place the symptoms are strongest in the beginning of the week, after the weekend, and they diminish during the week (Reinikainen 2002).

IEQ-allergy and asthma

A recent summary (IOM 2000) shows that symptoms of asthma and allergy may be triggered by number of allergens in indoor air which are related to building factors, such as ventilation and filtration rates, indoor humidity, space cleaning practices, presence of pets, and particularly to dampness problems in buildings (Bornehag et al. 2001). Viral respiratory infections, which may be influenced by ventilation rates, also appear to be linked to exacerbation of asthma.

IEQ-SBS

Characteristics of buildings and indoor environments have been linked to the prevalence of acute building related sick building syndrome symptoms experienced by building occupants. IEQ conditions linked to elevated prevalences of symptoms Mendell (1993) include high room air temperature, high concentration of dust on surfaces, and high airborne concentrations of certain groups of volatile organic compounds. Building characteristics linked to symptoms include low ventilation rates, carpets, air conditioning, etc. The problem in using these results is that studies express only statistically significant relationships, while dose response relationships that can be characterized mathematically is generally

needed for cost-benefit modeling. Approximate quantitative relationships could be developed between both ventilation rates and SBS symptoms and between temperatures and SBS symptoms.

Benefits

The potential benefits from improved IEQ include reduced medical care cost, working days gained due to reduced sick leave, better performance in work, lower turnover of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality. The pathways to these potential benefits from building technology and indoor environment go via the human responses described above.

It is self-evident that illnesses will cause sick leave and lost working days (#11). Performance at work (#12) is more complicated to quantify. Three distinct aspects of performance can be identified: quantity (speed), quality (e.g. number of mistakes), and group effect (e.g. how well group works together). The quantity of work has been used as a metric both in laboratory and full-scale experiments. In real buildings the measurement of work quantity and quality is easier for manual or routine work (e.g. processing forms) than for highly cognitive work. Improvements in personal environment improved also the self-evaluated group performance (Drake 1990).

The psychosocial character of a workspace, and related communications among employees, may also significantly impact work performance sick leave. Indoor environmental conditions may lead to complaints, but also to communications among employees. Technical questions on indoor environment are interrelated with the dynamics of the work community. If concerns are not addressed properly, communication problems may occur and rumors about indoor problem may be circulated widely. This may change the employees' attitude about the employer, and further change performance (Figure 2). Conflicts are common and may complicate the problem solving process (Lahtinen et al. 2002). Thus, the way complaints are dealt with in an organization may have an significant effect on the performance and productivity, modifying the relationship of IEQ with financial outcomes.

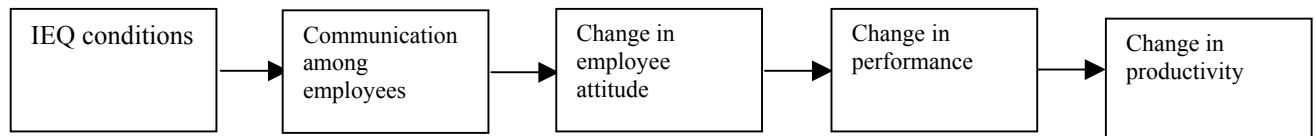


Figure 2 An organizational pathway from IEQ conditions to productivity

A reduced job turnover (#13) would significantly reduce costs to employers. 43 employees participated in a 1999/2000 benchmarking study on health, productivity and management program (Goetzel et al. 2001). The median estimate of these costs was \$9992 per employee per year, which is distributed among group health (47%), turnover (37%), unscheduled absence (8%), non-occupational disability (5%), and workers' compensation programs (3%).

Reduced responses of FM to complaints (#14) due to indoor air quality and thermal climate are considered an economic benefit as the facility management has to respond to many complaints. Federspiel (2001) reported that 18.4% of complaints were classified as indoor environmental complaints in a dataset which was collected from 575 buildings in the USA. 77% of indoor-environmental complaints were about conditions perceived too hot or too cold. He showed that the rate of complaints depends on the average room temperatures and its standard deviation in the building. He estimated the potential savings in the maintenance cost to be \$0.0035/ft² per year just due to reduced hot and cold complaints.

Benefits in the each benefit category depend on the type of work performed in the building. As a first approximation the value of the employees working time can be evaluated by using his/her salary with overheads. In more detailed analysis group performance should be assessed.

Linkage between human responses and potential benefits

Health care costs are affected by illnesses, however, it is questionable if the building owner or employer gets any benefit due to reduced direct health care costs. This depends on the health care system and the possible additional health care programs paid by employer.

Some of the links between human responses and financial benefits are obvious (e.g. illnesses are linked to health care cost and absence from work). Gained working days due to fewer sick leave days are clear benefits to the employer. Berger et al. (2001) concludes that employees' health is also related to work performance.

The link between prevalence of SBS symptoms and productivity seems to exist as summarized by (Fisk 2000). The number of SBS symptoms has been linked to self estimated productivity. The prevalence of SBS symptoms has also been linked to sick leave. However, a quantitative mathematical relationship of SBS symptoms to absence and work performance could not be determined, although analyses of some existing data sets might provide information on the SBS-absence linkage. The evidence which we have collected support the previous estimates on the effect of SBS-symptoms on sick leave and productivity. A summary of the studies establishing the linkage between SBS-symptoms, sick leave and performance is parented later in the paper.

Thermal conditions outside of the thermal comfort (or neutral) zone deteriorate performance in many tasks. The linkage between thermal environment and performance is probably the best established link between IEQ and human performance. The existing information on this linkage is summarized by Seppänen and Fisk (2004).

In some laboratory tests with ventilation rates and pollution loads (Wargocki et al. 2000) the perceived air quality (PAQ) has been correlated with performance. The estimated effect on performance based on typing, addition and proof reading tests was 1.5% per each 10% of dissatisfied people with air quality. This linkage, however, may overlap with the linkage between SBS and productivity as PAQ may also affect the prevalence of SBS as both are subjectively reported.

Investment and operational cost

The model includes the annual cost of investments, and operation costs. In this paper, however, we do not discuss these cost items in any detail, as the cost estimation of construction work and operation is a well-developed engineering practice in all industrialized countries.

Cost effectiveness

The cost effectiveness (Box #20) of the selected measure depends on the ratio of annual benefits, investment cost and difference of operational costs. The value of the money, taxes, subsidies etc. may affect on the final result.

PERSPECTIVE

The cost effectiveness of measures that improve the indoor environment varies depending on the perspective taken (e.g., building owner, employer, broader society) and occupancy. The model was developed first for owner occupied buildings when the benefits from the owners' and employers' view point are the same. The situation is different when the building is rented. Benefits from the improvements of the indoor environment may be transferred via the rent to building owner while the employer gets the benefits from the improved productivity. In general, neither the owner nor the employer benefit from reduced medical care costs which in many countries a part of social security system. From the lessor's perspective (Figure 3) the benefits are potentially higher rent, and the long term benefits related to the quality of the building: market value of the building space and ability to maintain lessees. The last one may be very important. Lewis (1992) estimated that if tenant does not renew the lease agreement at its end (e.g. due to frequent indoor air complaints) the costs of lost rental income, remodeling etc. to the owner of the building will be equivalent to one and half years rent. Less information is available how much quality of indoor environment affects the rent. However, the lease agreements should be developed to reflect also the indoor environment of the building. Van Kempski (2002) demonstrated with a simple calculation the benefits of good indoor environment for both lessor and lessee.

From the lessees' perspective, the benefits are the same as in owner occupied building. The lessee will generally not directly experience the costs of building design or operational changes. The owner receives the benefits from the reduced maintenance costs.

Economic IAQ model for the rented buildings from lessor's perspective

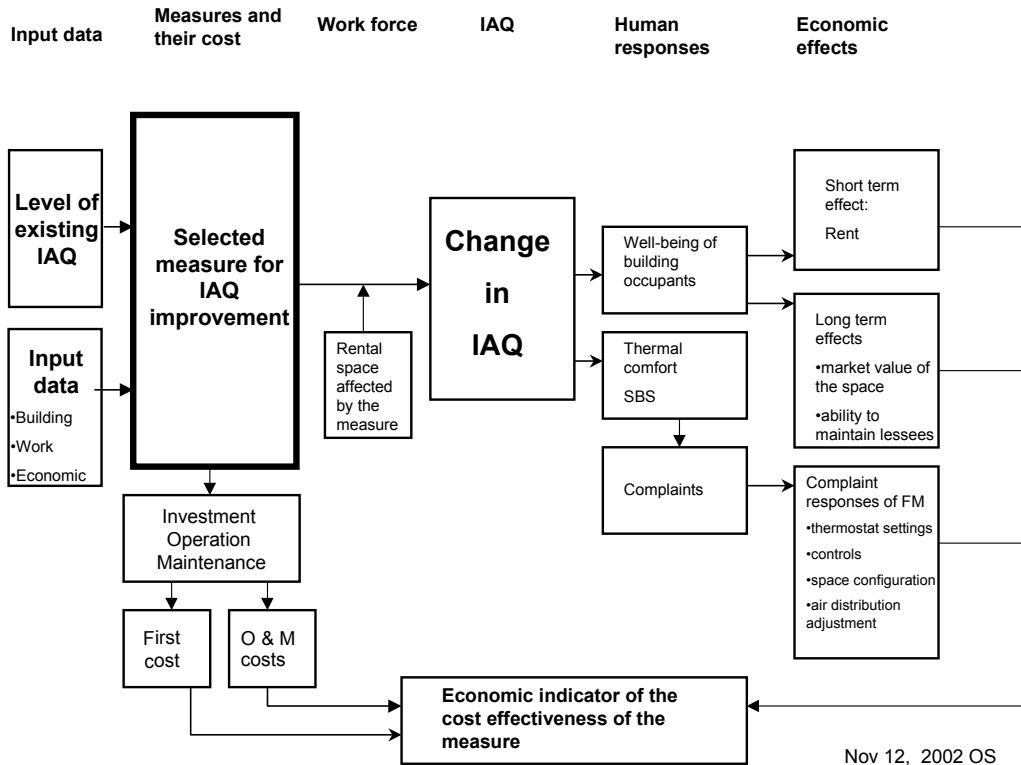


Fig 3 Conceptual model from lessor's (building owner's) perspective in leased building

LINKAGE BETWEEN SBS-SYMPTOM PREVALENCES, PRODUCTIVITY AND SICK LEAVE

SBS-symptoms are probably the most common metrics used to measure human responses in health related building investigations. Characteristics of buildings and indoor environments have been linked to the prevalence of building-related SBS-symptoms experienced by the occupants of the building. IAQ conditions linked to the elevated prevalence of symptoms include high room air temperature, high concentration of dust in room air and on surfaces, and high airborne concentrations of certain groups of volatile organic compounds. Building characteristics linked to symptoms include e.g. low ventilation rates, carpets and air conditioning.

For economical analysis in building refurbishment and improvements of indoor environment, it would be very useful if we could quantitatively relate the prevalence or intensity of SBS-symptoms to productivity.

We identified twenty three studies (table 1) which reported simultaneously prevalence or intensity of SBS symptoms and sick leave, absence from work or effect on productivity. From those, eight were field experiments and eleven cross sectional field studies. Eight of these field studies (Hall et al. 1991, Heslop 2002, Nordbäck et al. 1990, Preller et al. 1990, Hedge et al. 1993, Menzies et al. 1999, Teculescu et al. 1998, Robertson et al. 1990) reported an association between SBS symptoms and the amount of sick leave; however, the sick leave was generally self-reported on the same questionnaire used to assess SBS symptoms except by Robertson (1990).

Eleven field studies (either cross sectional or experimental) reported association between SBS-symptoms and self-assessed productivity in office environment (Chao et al. 2003, Hall et al. 1991, Hedge et al. 1993, Heslop 2002, Heslop 2003, Menzies et al. 1997, Rohr and Brightman 2003, Whitley et al. 1995, Woods and Morey 1987, Wyon et al. 2000). However, the validity of the self-reported productivity data is unclear. Only one cross sectional study by Niemelä et al. (2002) reported objectively measured productivity and SBS-symptoms in office environment. Another two studies reported association between SBS-

symptoms and objectively measured performance in school environment (Myhrvold et al. 1996, Myhrvold and Olesen 1997). Also, these data do not confirm that increased SBS-symptoms would be the cause of the decreased self-reported productivity.

In addition to field studies, four laboratory studies (Fang et al. 2002, Kaczmarczyk et al. 2002, Nunes et al. 1993, Wargocki et al. 2000) reported association between SBS-symptoms and objectively measured performance in tests related to productivity in office work. These studies report an association, but not necessarily a causal relationship, between increased SBS-symptoms and diminished objectively measured performance in tests that have tasks emulating real work. These studies are perhaps the strongest evidence of a productivity decrement and the primary basis for previous estimates of an overall 2% decrease in productivity due to SBS-symptoms (Fisk 2000; Mendell et al. 2002); however, the high level of uncertainty in this 2% estimate has been emphasised by the authors

Based on the reviewed studies, subjects who report more SBS symptoms also report more IEQ-related absence and IEQ-related decreases in productivity. However, the validity of the self-reported absence and productivity data is unclear. Also, these data do not confirm that increased SBS symptoms are the cause of the decreased self-reported productivity or increased absence. Also, even if all data were valid, in most cases the information provided does not enable us to develop a generalizable and quantitative relationship between SBS symptoms and performance or absence. The lack of standard SBS symptom, absence, and productivity metrics are one factor that impedes general conclusions. However, the number of the studies with the association between SBS-symptoms and productivity or sick leave suggests that such relationship exists.

TABLE 1
Studies assessing simultaneously the prevalence or intensity of SBS symptoms and
subjectively-reported of or objectively-measured productivity and absence outcomes by
study type.

Study type	Absence/sick leave		Productivity/performance	
	Self-reported (7)	Objectively recorded (1)	Self-reported (13)	Objectively recorded (5)
Cross sectional field study (11)	Hall et al. 1991, Heslop 2002, Nordbäck et al. 1990, Preller et al. 1990		Hall et al. 1991, Heslop, 2002, Raw et al. 1990, Whitley et al. 1995, Woods and Morey 1987, Rohr and Brightman 2003, Chao et al. 2003, Heslop 2003	Myhrvold et al. 1996
Experimental field study (8)	Hedge et al. 1993, Menzies et al. 1999, Teculescu et al. 1998	Robertson et al. 1990	Hedge et al. 1993, Menzies et al. 1997, Wyon et al. 2000	Myhrvold and Olesen, 1997, Niemelä et al. 2002
Laboratory experiment (4)			Fang et al. 2002, Kaczmarczyk et al. 2002	Nunes et al. 1993, Wargocki et al. 2000

DISCUSSION AND CONCLUSIONS

For cost-benefit analyses it is not sufficient to have information demonstrating a statistically-significant effect, the size of that effect must be quantified. Thus, we need quantitative functions for each of the arrows between the boxes in Figures 1 and 3. An absence of these quantitative functions is the primary barrier to performing cost benefit analyses, and is a major obstacle to better indoor environments.

To date, we are able to derived only a few quantitative functions, and even these functions have much uncertainty. The relationships of ventilation rates to absence and then between absence and absence-related

productivity losses have been estimated. The relationships of temperatures to work performance have been estimated for temperatures within and above the comfort zone. Also, Federspiel (2001) has estimated the relationship of temperatures to hot and cold complaints, and the costs of responding to these complaints have been estimated. A relation between SBS symptoms and both decreased productivity and increased absence is strongly suggested by the available data, but with the available data we chose not to propose a quantitative relationship for cost-benefit modeling. Special value would be more reliable functions relating SBS symptoms to absence and/or productivity because there is much data relating building design and operation to SBS symptom prevalences. Data relating SBS symptoms to independently-collected absence rates seems to be available in some data sets, but the association has not been analysed.

It is important to notice that when the benefits from the indoor environmental improvements are estimated that one cannot simply add the benefits of each separate indoor environmental improvement measure as their effects may overlap. For example, increased ventilation or increased filtration might both decrease illness rates, but the effects are not independent.

The quantitative relationship between a building feature or IEQ condition and productivity will often depend on other building features, and possibly on the characteristics of building occupants and their type of work. For example, increased ventilation rates may be highly beneficial in a building with strong indoor pollutant sources and only marginally beneficial in buildings with below-average pollutant sources. Remedial measures will generally be more cost effective in buildings that have poorer initial IEQ or more existing adverse health effects.

At the present we have, at best, rough estimates of the average quantitative relationships for the buildings selected for studies. Hence, uncertainty about the magnitude of benefits in a specific building will remain an obstacle, even when average benefits can be estimated. To the degree possible, the application of the cost-benefit model to evaluate design options or operational procedures in specific buildings should be performed using building specific data.

Currently we have mainly information on the effects of indoor environment and building factors on an average population or work force. We recognize that responses to IEQ will vary among individuals. Perhaps, only the more susceptible portion of the population may be adversely affected by poorer IEQ. Theoretically, it would be more cost effective to target the remedial actions on those who suffer most from indoor environmental conditions; however, such a targeted response will often be impractical. In some cases, however, a targeted measure is possible such as individual temperature control with local heaters. Individualized or task ventilation systems are another potential practical option, but further development of these systems is needed.

The market situation may also affect the potential benefits. A speculative builder may be interested only in the short term return of the investment. A lesser may let the indoor environmental quality of the building deteriorate by saving money on maintenance and accept (or be unaware of) the decrease in rental income and value of the property. In our model we have, however, assumed constant maintenance of building.

The potential productivity gains depend also on the type and size of the employer. An increase of performance is more important when the work is labor intensive, and may be more practical for large companies. For example a ten-person company would not be able to decrease its staff after an IEQ improvement that increased productivity by a few percent, while a company with hundreds or thousand of workers could adjust their workforce.

We acknowledge the high level of uncertainty associated with the incorporation of productivity in cost-benefit modelling related to building design and operation. However, we believe that estimating productivity benefits using the best available information will generally lead to better decisions about building design and operation than the current practice of ignoring the potential benefits.

Even though the cost-benefit model presented in this document is largely conceptual, we consider it a useful framework for the incorporation of productivity in cost-benefit comparisons of building designs and operating practices. We also consider the model useful for identifying and illustrating research needs. The model clearly illustrates the large need for more quantitative information so that the cost effectiveness of measures that improve indoor environments can be calculated.

ACKNOWLEDGEMENTS

This work was supported by the Finnish Technology Agency and Finnish Occupational Health Fund, project Productive Office 2005. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technology Program of the U.S. Department of Energy under

contract DE-AC03-76SF00098. The authors thank David Muddari, Mark Mendell, and Pawel Wargocki for their comments.

REFERENCES

- Berger M, Murray J, Xu J, Pauly M. 2001. Alternative valuations of work loss and productivity. *J Occup Environ Med.* 43:18-24.
- Bornehag C-G, Blomquist G, Gyntelberg F, Jarvholm B, Malmberg P, Nordvall L, Nielsen A, Perhagen G, Sundell J. 2001. Dampness in Buildings and health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to "dampness" in building and health effects (NORDDAMP) *Indoor Air Journal* 11:2:72-86.
- Chao HJ, Schwartz J, Milton DK, Muilenberg ML, Burge HA. 2003. Effects of indoor air quality on office workers performance – a preliminary analysis. In: *Proceedings of 7 th International Conference of Healthy Buildings 2003, Singapore.* Vol 3 pp. 237-243.
- Djukanovic, R. Wargocki, R, Fanger, P. 2002. Cost-benefit analysis of improved air quality in an office building. *Proceedings of Indoor Air 2002* pp. 808-813.
- Drake P. 1990. Summary of findings from the advanced design impact assessments. Centre of Building Diagnostics, (CANTECH) Ltd, Canada.
- Fang L, Wyon D, Clausen G, Fanger P. 2002. Sick building syndrome symptoms and performance in a field laboratory study at different levels of temperature and humidity. *Proceeding of Indoor Air 2002*, pp. 446-471.
- Federspiel C. 2001. Estimating the Frequency and Cost of Responding to Building Complaints In: Spengler, J. Sammet J. and McCarthy, J. eds. *Indoor Air Quality Handbook*, McGraw Hill
- Fisk WJ. 2001. Estimates of potential nationwide productivity and health benefits from better indoor environments: an update. In: Spengler, J. Sammet J. and McCarthy, J. eds. *Indoor Air Quality Handbook*, McGraw Hill.
- Fisk WJ. 2000. Health and productivity gains from better indoor environment and their relationship with building energy efficiency. *Annual review of the energy and the environment.* Vol 25. 2000, pp 537-566.
- Fisk WJ, Seppanen O, Faulkner D, Huang J. 2003. Economizer system cost effectiveness: accounting for the influence of ventilation rate on sick leave. Accepted for presentation at Healthy Buildings 2003, December 7 – 11 at the National University of Singapore.
- Fisk WJ, Seppänen O, Faulkner D, Huang J. 2004. Accounting for the influence of ventilation rate on sick leave in an analysis of economizer system cost effectiveness. A submitted manuscript to ASHRAE symposium Orlando 2005.
- Goetzel R, Guidon A, Turshen J, Ozminkowski R. 2001. Health and Productivity Management Establishing Key Performance Measures, Benchmarks, and Best Practices. *J occup Environ Med* 43:10-17.
- Hall H, Leaderer B, Cain W, Fidler A. 1991. Influence of building-related symptoms on self-reported productivity. *Proceedings of Healthy Buildings/IAQ 91 conference* pp 33-35.
- Hansen S-O. 1997. Economical consequences of poor indoor air quality and its relation to the total building operation costs. *EuroFM/IFMA Conference & Exhibition, Torino, Italy June 1997.*
- Hedge A, Mitchell G, McCarthy J, Ludwig J. 1993. Effects of a furniture-integrated breathing zone filtration system on indoor air quality, sick building syndrome, productivity and absenteeism, *Proceeding of Indoor Air 93* Vol 5, pp. 383 –388.
- Heslop K. 2002. Personal and environmental characteristics, occupational factors and psychosocial correlates of sick building syndrome. *Proceedings of Indoor Air 2002*, pp. 432 – 437.
- Heslop K. 2003. The influence of sick building syndrome on self-reported productivity and work disruption amongst office employees in two buildings in South Africa. In: *Proceedings of 7th International Conference of Healthy Buildings 2003, Singapore.* Vol 3, pp. 387-292.
- IOM. 2000. Committee on the Assessment of Asthma and Indoor Air. *Clearing the air. Asthma and indoor exposures.* National Academy of Science, Institute of medicine. National Academic Press. Washington DC.
- Jaakkola JJ, Heinonen OP. 1995. Shared office space and the risk of the common cold. *Eur J Epidemiol* 1995 Apr;11(2):213-216.

- Kaczmarczyk J, Zeng Q, Melikov A, Fanger PO. 2002. The effect of a personalized ventilation system on perceived air quality and SBS symptoms. In *Indoor Air 2002: Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol 4, H Levin, ed., Indoor Air 2002, Santa Cruz, California, pp. 1042 – 1047.
- van Kempski. 2002. Increasing the value of a building by addressing well being – the principal tools: thermal and olfactory comfort, *Proceedings of Indoor Air 2002*, pp 678-683.
- Lahtinen M, Huuhtanen P, Kahkonen E, Reijula K. 2002. Psychosocial dimensions of solving an indoor air problem. *Indoor Air Journal* 12:33-46.
- Lewis F. 1992. The cost of office workers discomfort. *Enviros, The healthy building newsletter*, Vol 2, 4.
- Mendell M. 1993. Non-specific symptoms in office workers: A Review and summary of the epidemiological literature. *Indoor Air Journal* 3:227-236.
- Mendell MJ, Fisk WJ, Petersen MR, Hines CJ, Dong M, Faulkner D, Deddens JA, Ruder AM, Sullivan D, Boeniger MF. 2002a Indoor particles and symptoms among office workers: results from a double-blind cross-over study. *Epidemiology* 13: 296-304.
- Mendell M, Fisk WJ, Kreiss K, Levin H, Alexander D et al. 2002. Improving the health of workers indoor environments: Priority research needs for a national of occupational research agenda, *American Journal, of Public Health*, Vol 92, No 9, pp. 1430-1440.
- Menzies D, Pasztor J, Rand T, Bourbeau J. 1999. Germicidal ultraviolet irradiation in air conditioning systems: effect of office worker health and wellbeing: a pilot study. *Occup Environ Med Jun*: 56(6):397-402.
- Menzies D, Pasztor J, Nunes F, Leduc J, Chan C. 1997. The effect of a new ventilation system on health and well being of office workers. *Arch. Environ. Health* 52 (5): 360-67.
- Milton K, Glenross P, Walters M. 2000. Risk of Sick leave associated with outdoor air supply rate, humidification, and occupant complaint. , *International Journal of Indoor Air Quality and Climate*. 10 :211-221.
- Myhrvold A, Olsen E, Lauridsen O. 1996. Indoor environment in schools / pupils health and performance in regard to CO₂ concentrations, *Indoor Air* 1996, Vol 4,: 369 – 374.
- Myhrvold A, Olesen E. 1997. Pupils health and performance due to renovation of schools. *Proceeding s of Healthy Buildings/IAQ 1997*. 1:81-86.
- Nardell EA, Keegan J, Cheney SA et al. 1991. Theoretical limits of protection achievable by building ventilation. *American Review of Respiratory Disease*. Vol. 144, pp. 302-306.
- Niemela R, Hannula M, Rautio S, Reijula K, Railio J, 2002. The effect of indoor air temperature on labour productivity in call centers – a case study. *Energy and Buildings*. 34 :759-764.
- Nordbäck D, Ingegard M, Widström J. 1990. Indoor air quality and personal factors related to the sick building syndrome. *Scandinavian J Work Environ Health* 1990;16:121-128.
- Nunes F, Menzies R, Tamblyn R, Boehm E, Letz R. 1993. The effect of varying level of outdoor air supply on neurobehavioural performance function during a study of sick building syndrome (SBS). *Proceedings of Indoor Air '93*, Vol. 1, pp. 53-58.
- Preller L, Zweers T, Brunekreef B, Boleij JSM. 1990. Sick leave due to work related complaints among workers in the Netherlands. *Proceedings of Indoor Air 1990* 1:227-230.
- Raw G, Roy M, Leaman A. 1990. Further findings from the office environment survey. *Proceedings of Indoor Air 90 conference*, vol 1, pp. 231-236.
- Rohr AC, Brightman H. 2003. Effects of characteristics on self-reported productivity of office workers: the base study. In: *Proceedings of 7th International Conference of Healthy Buildings 2003, Singapore*. Vol 3, pp. 231-236.
- Reinikainen L. 2002. Indoor air humidification, sick building syndrome symptoms, and perceived indoor air quality in the office environment. PhD thesis. Report A6. Laboratory of Heating , Ventilating and Air Conditioning. Helsinki University of Technology.
- Riley E. 1980. The role of ventilation in the spread of measles in elementary school. *Annals New York Academy of Sciences* pp. 25-34.
- Robertson AS, Roberts KT, Burge PS, K. Raw G. 1990. The effect of change in building ventilation category on sickness absence rates and the prevalence of sick building syndrome. *Proceedings of Indoor Air '90*, pp. 237-242.

- Seppänen O. 1999. Estimated cost of indoor climate in Finnish buildings. *Proceedings of Indoor Air 1999*. Vol 3, pp. 13-18.
- Seppänen O, Fisk WJ, Faulkner D. 2004. Control of temperature for health and productivity in offices. A submitted manuscript to ASHRAE Symposium in Orlando, 2005.
- Seppänen O, Fisk W, Mendell M. 1999. Association of Ventilation Rates and CO₂ Concentrations with Health and other Responses in Commercial and Institutional Buildings. *International Journal of Indoor Air Quality and Climate*. 9:226-252.
- Seppänen O, Vuolle M. 2000. Cost effectiveness of some remedial measures to control summer time temperatures in an office building. *Proceedings of Healthy Buildings 2000*.
- Teculescu D, Sealeau E, Massin N, Bohadana A, Buhler O, Benamghar L, Mur J. 1998. Sick-building symptom in office workers in northeastern France: a pilot study. *Int Arch Occup Environ Health* Jul;71(5):353-6
- Tuomainen M, Smolander J, Kurnitski J, Palonen J, Seppanen O. 2002. Modelling of the cost effects of indoor environment. *Proceedings of Indoor Air 2002*, pp. 814-819.
- Wargocki P, Wyon D, Fanger O. 2000. Pollution source control and ventilation improve health, comfort and productivity. *Proceedings of Cold Climate HVAC 2000*, Sapporo, Japan, 2000, pp. 445-450.
- Wargocki P, Wyon D, Sundell J, Clausen G, Fanger O. 2000. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity, *International Journal of Indoor Air Quality and Climate*. 10 :222-236.
- Whitley T, Makin P, Dickson D. 1995. The environment, comfort and productivity: the role of individual differences including locus of control. *Proceedings of Healthy Buildings '95*. vol 3, pp. 1419–1424.
- Woods J, Morey G. 1987. Office workers perception of indoor air quality effects on discomfort and performance, *Proceedings of Indoor Air 1987* 2:464-468.
- Wyon D, Tham K, Crocford A, Oreszczyn T. 2000. The effect on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises. *Proceedings of Healthy Buildings 2000 Conference*, Vol 1, pp. 641-646.